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Micro-Cavity Integrable Vacuum Diodes and Triodes

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DISCLAIMER

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ABSTRACT: We are developing miniature, vacuum, field emission diodes, and triodes for use in electronics in hazardous environments. We have produced the structures for micrometer sized diodes and triodes. We are currently improving the emission rate of the field emission electron source, before inserting it into the diode and triode structures.

1. INTRODUCTION

Miniature vacuum diodes and triodes are micrometer sized, silicon, electronic switching and control devices with a vacuum as the active volume instead of silicon. They are fabricated on silicon wafers using much the same processing techniques as are used for solid-state integrated circuits, making them completely compatible with existing integrated circuit technology. This makes possible the eventual integration of miniature vacuum tubes with existing integrated circuit components. We use the sacrificial layer technique to produce the free standing structures (Orvis 1989).

2. FABRICATION OF A VACUUM TRIODE

First, coat the surface (100) of the silicon wafer with an isolation layer consisting of 0.5 μm of silicon dioxide and 0.4 μm of silicon nitride. Create the field emitters with an anisotropic etch behind a square mask of silicon nitride 800 Å thick. Fill the cavity containing the field emitter with low density glass and reflow the glass to planarize it. Pattern a layer of doped polysilicon to create the grid structure. Bury the grid structure in more low density glass. Pattern another layer of doped polysilicon to form the anode. Finally, remove the low density glass using hydrofluoric acid. The resulting structure, with the free standing anode and grid, is shown in Figures 1, and 2.

Figure 3 shows a vacuum diode with the anode structure broken loose and flipped over. The vacuum diode is a simple variation of the triode design, which leaves out the polysilicon grid.

3. TESTING AND PROBLEMS

Progress in this project has been delayed by seemingly minor processing problems that often required a complete rebuilding of the device to correct. Most of the processing problems are related to the sacrificial layer technique, and the long etch times associated with it. First, we had adhesion problems of the photoresist on the glass layers. The photoresist would come loose at the edges and allow etching to go on beneath it. We corrected this problem by using patterned chrome as a mask for the glass.

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Next, the silicon dioxide isolation layer under the bond pads was damaged by the long processing times for the sacrificial layer. When wires were attached to the pads, they tended to short to the substrate. We changed the isolation layer to silicon nitride, but Frenkel-Poole conduction in the silicon nitride obscured any field emission (Sze 1981). Frenkel-Poole conduction in silicon nitride is difficult to tell from field emission by the shape of the current versus voltage curve. However, it can be identified by the fact that it is bidirectional and temperature sensitive.

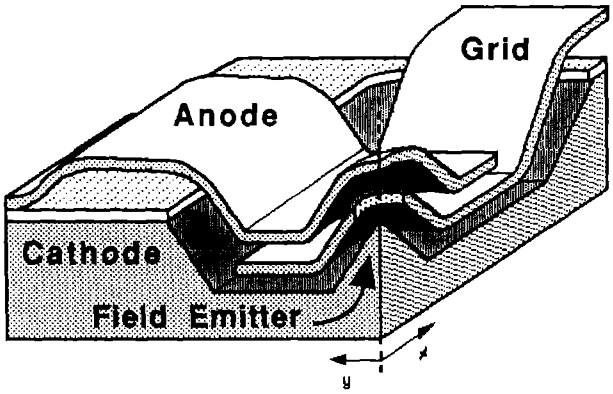


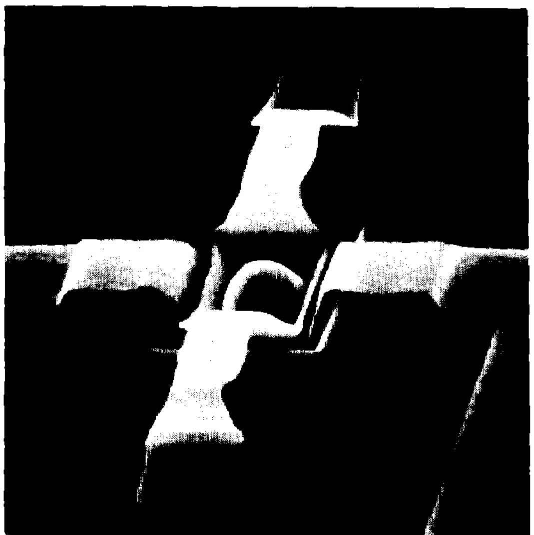
Figure 1 A cutaway section of the vacuum triode showing the field emitter, grid and anode.

We corrected this problem by first coating the wafer with silicon dioxide (0.5 μm), and then with silicon nitride (0.4 μm). Bond pads placed over this isolation layer can now withstand wirebonding without shorting and can hold off over 500 V without breaking down.

Our next problem involved shorting of the anode structure to the cathode due to electrostatic attraction. We applied 300 V across a vacuum diode and observed anomalous currents that would erratically turn on and off. It turns out that the electrostatic attraction between the anode and the substrate was sufficient to bend the anode down until it touched the substrate, causing a short and also collapsing the field. When the field collapsed, the anode would spring back and break the connection, creating the switching of the current.

There are two ways to correct this problem, the first is to stiffen the anode structure, and the second is to make the field emitters operate at a lower voltage. We are stiffening the anode by thickening it, and are currently working on the emission rate of our field emitters.

From discussions with other researchers, it appears that our field emission tips need to be sharper by a factor of about 2. Initially, we created our tips by anisotropic etching of silicon with ethylenediamine-pyrocatechol-water (EPW). EPW is hard to control, and resulted in tips with a radius of curvature on the order of 1000 Å. We have changed to potassium hydroxide buffered



I.....25 μ.....I

Figure 2. Electron-micrograph of the vacuum triode. the horizontal structure is the grid and the vertical structure is the anode. The field emitter is under the hemispherical section at the center of the anode.

I......20 μ......I

Figure 3 Electron-micrograph of the vacuum diode with the anode broken off and flipped over to show its underside, and the field emitter.

with secondary butyl alcohol, which is slower, but much more controlled, resulting in tips with a curvature of less than 500 Å. Using a field of emitters created with this process, we achieved field emission with an applied voltage of 40 V across a 2 μm vacuum gap (Figure 4).

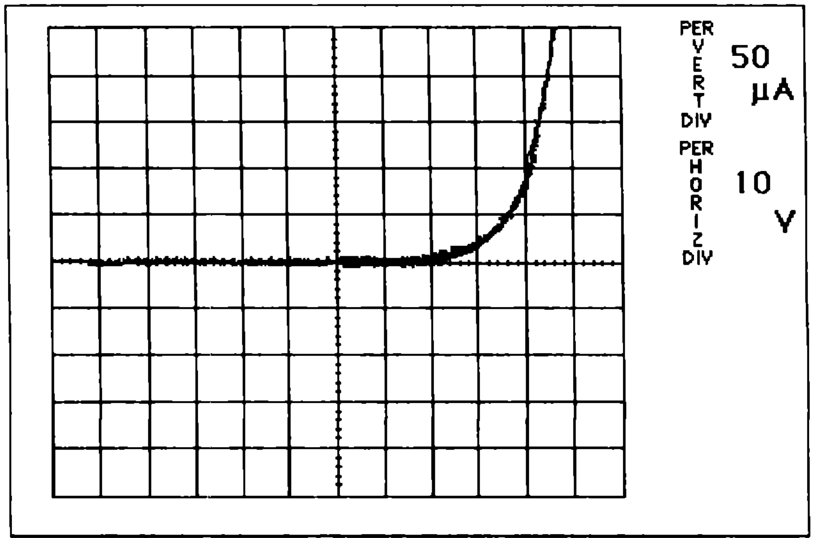


Figure 4 Current versus voltage curves for a field of 10,000 to 15,000 field emitters spaced two micrometers from an anode.

We are currently undertaking a systematic study of anisotropic etching of (001) silicon with various formulations of potassium hydroxide and water, mixed with alcohol, to obtain field emission points. The results show that uniform arrays of field tips, having eight {331} facets, can be obtained with solutions mixed with secondary or tertiary-butyl alcohols. These results are presented elsewhere (Hunt 1989).

We are applying these eight-sided field emission tips to the new dimpled diode structure, shown in Figure 5. The point is overcoated with a 1 um sacrificial layer of spin-on glass. The glass is thinned, or dimpled over the tip and then the structure is overcoated with evaporated tungsten. After the tungsten is patterned to become the anode and the interconnect/pad layer, the glass layer is removed completely, leaving an air-bridge structure. Because the thinning of the glass can be controlled with precision, using reactive ion etching, the final cathode-anode spacing is uniform across the entire wafer and can be changed, if desired, without requiring a new mask.

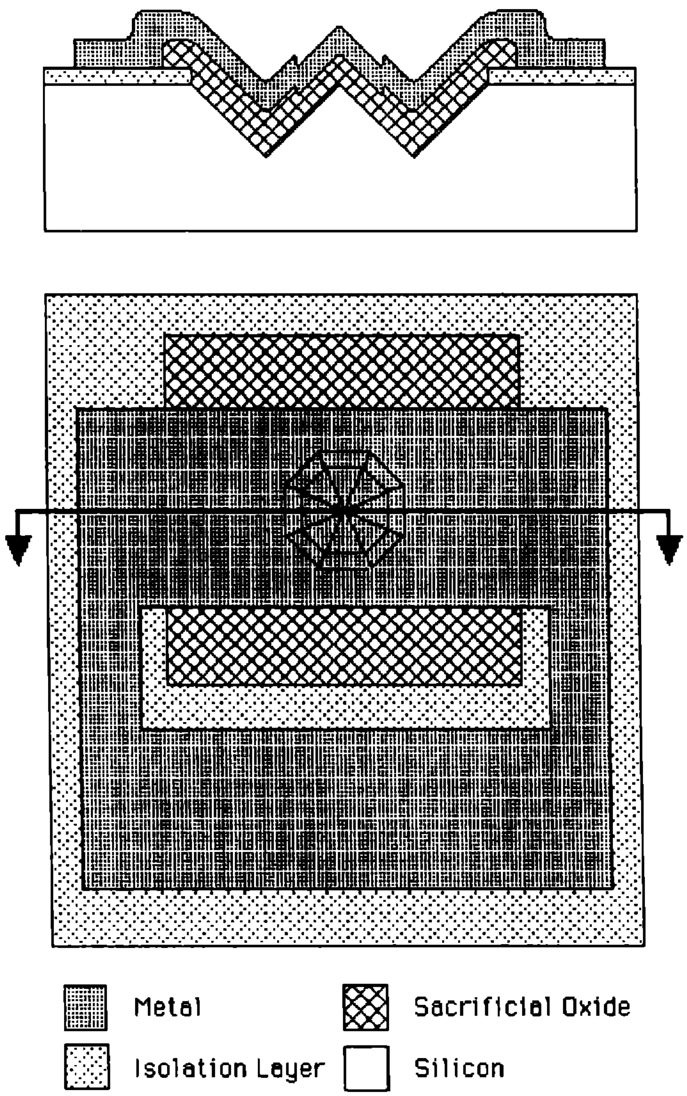


Figure 5: Cross section and top view of the dimpled diode structure.

4. MODELING

Using the combination of a two-dimensional static field modeling code, and the theoretical Fowler-Nordheim equation, we have estimated the operating characteristics of our vacuum triode (Figure 6). The curves were created by fitting the field at the tip of the field emitter, calculated with the static field modeling code, versus the voltage on the anode and grid. The resulting equation is inserted into the

Fowler-Nordheim equation to calculate the current-voltage characteristics. By taking the appropriate derivatives of the current -voltage curve (see Orvis 1989), we obtain the tube parameters. Note that these tube parameter values are not typical of those expected from more traditional vacuum tubes. The plate resistance is high, the transconductance is low, and the static gain is low. These differences must be taken into account when designing circuits for these devices.

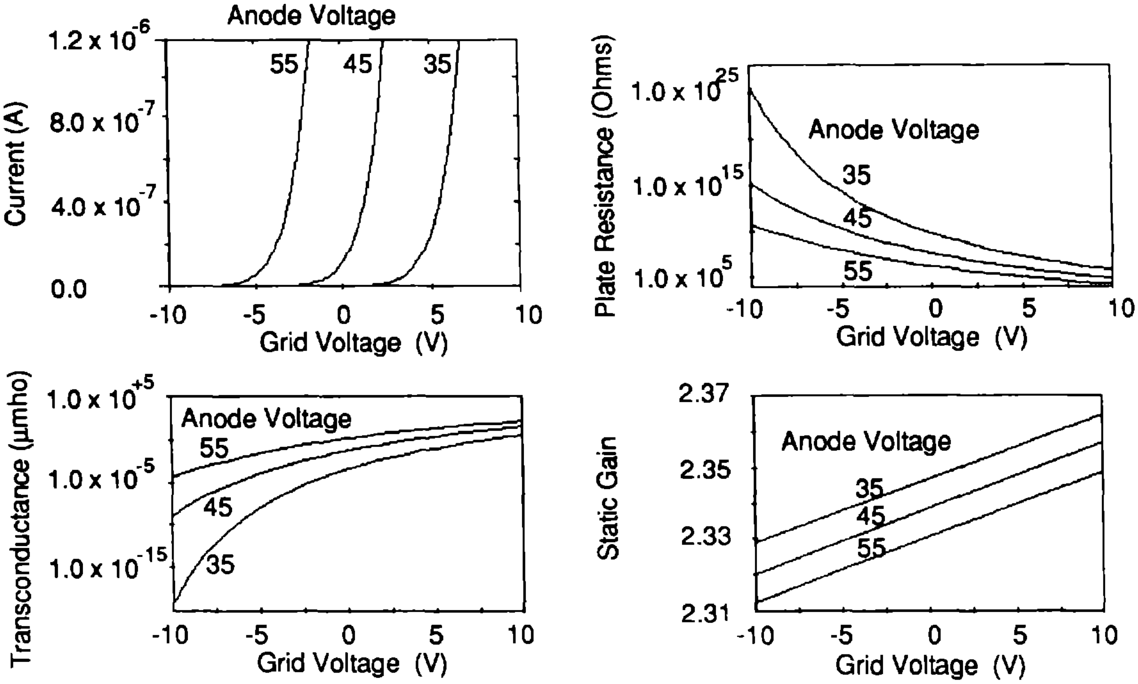


Figure 6 Theoretical current-voltage, plate resistance, transconductance and static gain curves for the miniature vacuum triode. These assume a 1.5 micrometer anode to cathode distance, the tip of the cathode is centered in a 1 micrometer radius hole, and even with the top of the grid, the emission area is 0.2 micrometers in diameter and the field at the tip has an additional enhancement factor of 20 due to microstructure on the tip.

5. CONCLUSION AND PLANS

We have completed the structures for a field emission diode, and triode, and are currently enhancing the field emission rate of our field emitters. When we are satisfied with the emission rate, we will insert the field emitters into our diode and triode structures, and evaluate the performance of the resulting devices. We are also considering a new anode structure that will allow more precise control of the anode to cathode spacing.

6. REFERENCES

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